APPLICATION
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OPTICAL MODULE

BACKGROUND OF THE INVENTION

The present invention relates to an optical module having
a structure in which an input side and an output side disposed
to be separated from each other by a free space are optically

5   coupled to each other through an optically functional portion
inserted between the input side and the output side. In more
detail, it relates an optical module in which at least one of
the input side and the output side has a plurality of collimators
at least one of which is made different from the other collimators

10   in at least one variable characteristic parameter to thereby
achieve optimum optical coupling between the input side and the
output side. For example, the present invention is useful for
a matrix optical switch, an optical multiplexer/demultideplexer,
an optical tap, and so on.

15   As well known, a collimator is used in an optical technology
in order to convert divergent light from an exit surface of a
light-emitting device or an optical fiber to approximately
collimated beams, or contrariwise in order to converge the
collimated beams on an incident surface of a photodetector or

20   an optical fiber. When two or more collimators as described
above are disposed and an optical device of any kind is inserted
in a free space through which the magnified beams pass, an optical

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module can be formed.

In such an optical module, in many cases, the beam diameter may be small and the free space lengths between channels or ports may different from one another in accordance with the channels.

5   In the background art, however, coupling characteristic of the collimators is not optimized in such a case. For example, a collimator array had a structure in which a required number.of collimators of the same kind were simply arranged side by side at regular intervals (so as to make the distance between optical

10   axes of adjacent collimators equal to one another).

If an optical module is configured by use of collimators of the same kind in the case where free space lengths between channels or ports are different from one another, it is however difficult to achieve low insertion loss and low insertion loss

15   deviation even within a light diffraction limit. There, however, arises a problem that low insertion loss and low insertion loss deviation is hardly achieved even in a diffraction limited of the light so that the size of the optical module can hardly be reduced. This problem is caused by the fact that optical coupling

20   cannot be optimized in accordance with channels or ports, the fact that loss is constrained severely so that further light diffraction loss due to small beams used cannot be allowed, the fact that small-size collimators cannot be used in spite of channels or ports small in free space, and so on.

25   SUMMARY OF THE INVENTION

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An object of the present invention is to provide various
kinds of optical modules small in size, low in insertion loss
and low in insertion loss deviation in the case where free space
lengths are different from one another between channels or ports.

5   According to the present invention, there is provided an
optical module constituted by a light input side, a light output
side disposed to·be separated by a free.space from the.input
side, and an optically functional portion inserted between the
input side and the output side so that the input side and the
10   output side are optically coupled to each other through the
optically functional portion.   In the present invention, at least
one of the input side and the output side includes.a plurality
of collimators; and at least one of the collimators is made different
from the other collimators in at least one variable characteristic
15· parameter selected from parameters such as·a distance between
a focal point of a lens and a light exit or.incident surface,
a numerical· aperture of the light exit or incident surface, an
effective focal length of the lens, a wavelength used and a distance
between optical axes of adjacent ones of the collimators, so
20   that size and position of a beam waist on the input side are
made approximately coincident with those on the output side.
Here, the light exit surface means a light-emitting surface of
a light-emitting device, an end surface of an optical fiber,
or the like, whereas the light incident surface means a
25   photodetection surface of a photodetector, an end surface of

an optical fiber, or the like.

In the case where a plurality of optical fiber collimators each constituted by a combination of a lens and an optical fiber are provided on at least one of the input side and the output

5   side, at least one of the fiber collimators is made different from the other fiber collimators in at least one variable characteristic parameter selected from parameters such as a distance between a focal point of a lens and an end surface of the optical fiber, a mode field diameter or numerical aperture

10 of the optical fiber, an effective focal length of the lens, a wavelength used and a distance between optical axes of adjacent ones of the fiber collimators, so that size and position of a beam waist on the input side are made approximately coincident with those on the output side.

15 Hence, such a plurality of fiber collimators may be provided only on the input side or only on the output side or may be provided on both the input side and the output side. When the plurality of fiber collimators are provided only on the input side, the output side may be constituted by a combination of a collimator

20 lens and a photodetector. When the plurality of collimators are provided only on the output side, the input side may be constituted by a combination of a light-emitting device and a collimator lens. Alternatively, configuration may be made without using any fiber collimator so that the input side is

25 constituted by a combination of a light-emitting device and a

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collimator lens whereas the output side is constituted by a
combination of a collimator lens and a photodetector.

For example, there is a configuration in which the plurality
of collimators disposed on at least one of the input side and

5   the output side have a lens array constituted by a plurality
of gradient index rod lenses. In the case of having such a
configuration, either or each of opposite end surfaces of the
lens array is provided as an oblique surface with respect to
a direction of arrangement of the array to thereby adjust the

10   variable characteristic parameter. Further, in the case where
the plurality of fiber collimators are disposed on at least one
of the input side and the output side, there is a configuration
in which the plurality of fiber collimators are constituted by
a combination of a lens array of a plurality of gradient index

15   rod lenses and a fiber array of a plurality of optical fibers.
In the case of having such a configuration, either or both of
opposite end surfaces of the lens array and/or an end surface
of the fiber array are provided as oblique surfaces with respect
to a direction of arrangement of the array to thereby adjust

20   the variable characteristic parameter. Further, it is effective
to allocate longer wave to a channel longer in free space length.

Specifically, for example, collimators are provided on each
of the input side and the output side, the collimators on the
output side are disposed at an angle of 90 degrees with respect

25   to the collimators on the input side, and a movable mirror is

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inserted in a position corresponding to each channel in the free

space, so that a matrix optical switch can be formed. In such

a case, it is desirable to have a configuration in which points

of intersection between optical axes of the input side and optical

5   axes of the output side are set to be equivalent to lattice points

of a square lattice, movable mirrors are disposed at the lattice

points respectively, and adjustment is made so that beam waists

are formed on a diagonal line of the square lattice.

In the configuration in which the input side and the output

10   side disposed to be separated from each other by a free space

are optically coupled to each other through an optically functional

portion inserted between the input side and the output side,

an optical device constituted by either of a filter and a

semi-transparent mirror is used as the optically functional portion,

15   and adjustment is made in such a manner that beam waists as equal

to one another as possible are formed on the optical device.

In such a manner, an optical multiplexer/demultiplexer or an

optical tap can be formed.

For example, a fiber collimator with two fibers is disposed

20   on one side whereas a fiber collimator with single fiber is disposed

on an opposite side to the side, a filter is provided as the

optical device in a free space, one of optical fibers in the

fiber collimator with two fibers is provided as an input side

whereas the other optical fiber is provided as an output side,

25   an optical fiber in the collimator with single fiber is provided

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either as an input side or as an output side, and adjustment
is made in such a manner that beam waists as equal to one another
as possible are formed on a filter surface. In such a manner,
an optical multiplexer or an optical demultiplexer can be formed.

5   Further, a fiber collimator with two fibers is disposed on one
side whereas a fiber collimator with single fiber is disposed
on the opposite side, a semi-transparent mirror is provided as
an optical device in a free space, one of optical fibers in the
fiber collimator with two fibers is provided as an input side

10   whereas the other optical fiber is provided as an output side,
an optical fiber in the collimator with single fiber is provided
as an output side, and adjustment is made in such a manner that
beam waists of the fiber collimators as equal to one another
as possible are formed on the semi-transparent mirror. In such

15   a manner, an optical tap can be formed.

      The present disclosure relates to the subject matter contained
in Japanese patent application No. 2000-303813 (filed on October
3, 2000), which is expressly incorporated herein by reference
in its entirety.

20   BRIEF DESCRIPTION OF THE DRAWINGS
      Fig. 1 is an explanatory view of a fiber collimator coupling
system.
      Figs. 2(A) to 2(C) are explanatory views showing examples
of a collimator array constituted by a combination of a fiber

25   array and a lens array.

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Fig. 3 is an explanatory view showing an example of an optical module according to the present invention.

Fig. 4 is an explanatory view showing another example of the optical module according to the present invention.

5   DESCRIPTION OF THE PREFERRED EMBODIMENT

As described above, variable characteristic parameters in each collimator are the distance between the focal point of the lens and the light exit or incident surface, the numerical aperture of the light exit or incident surface, the effective focal length
10   of the lens, the wavelength used and the distance between the optical axes of adjacent collimators. In the case of fiber collimators, as described above, the variable characteristic parameters thereof are the distance between the focal point of a lens and an end surface of an optical fiber, the mode field
15   diameter or numerical aperture of the optical fiber, the effective focal length of the lens, the wavelength used and the distance between the optical axes of adjacent fiber collimators.

Here, a method of setting those variable characteristic parameters will be described below in the case where the input
20   side and the output side are constituted by fiber collimators respectively by way of example. As shown in Fig. 1, in a fiber collimator coupling system in which a pair of fiber collimators 14 each constituted by a combination of an optical fiber 10 and a lens 12 are arranged to face each other, equations of propagation
25   from a spot size 2w to a beam waist 2W which expresses basic

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characteristic are as follows.

$D = f^2d/(d_m^2 + d^2)$

$W = wf/(d_m^2 + d^2)^{1/2}$

In the equations, $\underline{f}$ is the effective focal length of each lens,
5 d_m is equal to $\pi w^2/\lambda$, and λ is the wavelength. To make optical
coupling good, the position and size of the beam waist in one
fiber collimator is made coincident with those in the other fiber
collimator. Hence, when the distance $\underline{d}$ between the optical fiber
and the focal length of the lens, the spot size $\underline{w}$ of the optical
10 fiber, the focal length $\underline{f}$ of the lens and the wave length λ are
changed, optimization of coupling efficiency can be attained.

 For example, to enlarge the distance D between the focal
point of the lens and the position of the beam waist, at least
one of the following conditions is selected.

15 (1) large $\underline{d}$ in a range of $0 < d < d_m$

(2) small $\underline{d}$ in a range of $d_m < d$

(3) small $\underline{w}$

(4) large $\underline{f}$

(5) large λ

20 Because there is a tendency that the effective focal length
$\underline{f}$ increases as the wavelength λ increases, the distance D (between
the focal point of the lens and the position of the beam waist)
increases more greatly if the wavelength λ increases. Therefore,
parameters are allocated to channels or ports long in free space
25 so that the distance D increases as described above.

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Any suitable lens can be used as the lens used in each of
the collimators. The lens may be a convex or spherical lens
made of a homogeneous material or may be a gradient index rod
lens. As described above, in the case of fiber collimators,

5   adjustment is made so that at least one channel differs from
the other channels in at least one variable characteristic
parameter selected from parameters such as the distance between
the focal point of the lens and the end surface of the optical
fiber, the mode field diameter or numerical aperture of the optical

10   fiber, the effective focal length and size (inclusive of the
distance between optical axes of adjacent fiber collimators).
In any case, collimators of the same kind may be used in part
of the channels. If each variable characteristic parameter is
changed, it may be theoretically possible in some cases and

15   theoretically impossible in other cases to make the sizes and
positions of the beam waists completely coincident with each
other in the whole of the optical module. In the case where
it is theoretically possible, the sizes and positions of the
beam waists are made as coincident as possible in terms of tolerance

20   and assembling accuracy of parts. Even in the case of theoretically
impossible combination, it is preferable that the state is made
as close to the ideal state as possible.

Figs. 2(A) to 2(C) show examples of adjustment of the variable
characteristic parameters. These examples show the case where

25   a lens array 20 constituted by a plurality of gradient index

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rod lenses is combined with a fiber array 24 constituted by a
plurality of optical fibers 22. Fig. 2(A) shows an example in
which an end surface of the fiber array 24 is polished obliquely
with respect to the direction of arrangement of the array. Fig.

5 2(B) shows an example in which an end surface (facing the fiber
array) of the lens array 20 is polished obliquely with respect
to the direction of arrangement of the array. In such a manner,
the distance between the focal point of each lens and the end
surface of a corresponding optical fiber can be adjusted. Fig.

10 2(C) shows an example in which the other end surface of the lens
array 20 is polished obliquely with respect to the direction
of arrangement of the array. When each lens is a gradient index
rod lens, the distance between the focal point of the lens and
the end surface of the optical fiber can be adjusted also in

15 this manner. When an oblique surface is provided as described
above, there arises an effect that the intensity of light fed
back to the optical fiber is attenuated. Incidentally, when
the quantity of attenuation is intended to be made larger, an
oblique surface with respect to a direction perpendicular to

20 the direction of arrangement of the array may be preferably provided.

In this case, the angle of the inclined surface with respect
to a plane perpendicular to the optical axis is preferably set
to be in a range of from 1 to 20 degrees. The structure in which
an end surface of the lens array is provided as an oblique surface

25 as shown in Fig. 2(B) or 2(C) can be applied also to the case

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where the lens array is combined with a light-emitting device or a photodetector without using any optical fiber.

In each of the examples shown in Figs. 2(B) and 2(C), a rod lens array 20 is in the form of a wedge shape, and constructed

5   by a plurality of gradient index rod lenses 20a arrayed in at least one row (in each example, arrayed in one row), and each extending in parallel to an optical axis direction; and a frame 20b supporting the gradient index rod lenses 20a. The frame 20b has a first end surface perpendicular to the optical axial

10   direction, and a second end surface inclined with respect to the optical axial direction. An end surface of each of the gradient index rod lenses 20a is flush with the second end surface of the frame 20b. An opposite end surface of each said gradient index rod lens 20a is flush with the first end surface of said

15   frame 20b. In the example shown in Fig. 2(B), the inclined second end surface of the frame 20b and the inclined end surfaces of the gradient index rod lenses 20a are confronted with the end surface of the fiber array 24. In the example shown in Fig. 2(C), the inclined second end surface of the frame 20b and the

20   inclined end surfaces of the gradient index rod lenses 20a are located opposite from the end surface of the fiber array 24. In addition, in the example shown in Fig. 2(C), the lens array 20 and the fiber array 24 may be formed integrally by using a common frame.

25   In the case of a gradient index rod lens with a length L,

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the refractive-index profile in the direction of the radius
(distance r) is given by the following expression:

$$n(r) = n_0(1 - Ar^2/2)$$

The effective focal length f is given by the following expression:

5    $$f = 1/(\sin(LA^{1/2})n_0A^{1/2})$$

in which $A^{1/2}$ is a coefficient of refractive index distribution.

Hence, in the configuration shown in Fig. 2(B) or 2(C), the
effective focal length f can be also adjusted in the same manner
as described above. Alternatively, the lens lengths may be

10   equalized to one another if n_0 or $A^{1/2}$ in at least one channel
can be made different from those in the other channels.

To change the mode field diameter or numerical aperture
of a fiber collimator, there is a method of changing the kind
of the optical fibers or heating and deforming end portions of

15   the optical fibers to magnify the end portions. When the respective
variable characteristic parameters are changed, the size of parts
used is changed. As a result, there arises a secondary effect
that the size of the optical module is reduced. When a planar
microlens array or the like is used as an array of lenses, the

20   shape of a mask or mold for forming each of the lenses is changed
to thereby adjust the effective focal length or size (including
the pitch for arrangement of the lenses).

[Examples]

Fig. 3 is an explanatory view showing an example of the

25   optical module according to the present invention. This example

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shows the case where the present invention is applied to a 4x4

matrix optical switch. Two collimator arrays 30, which serve

as the input side and the output side respectively, are arranged

at angles different by 90 degrees from each other. Movable mirrors

5   32 are inserted in respective positions corresponding to channels

in a free space. Each of the collimator arrays 30 has a structure

in which a fiber array and a lens array are integrated with each

other. The fiber array is constituted by four optical fibers

34 arranged side by side. The lens array is constituted by four

10   gradient index rod lenses 36 arranged side by side. Here, in

the respective channels, the position and size of the beam waist

on an input side are made as coincident with those on an output

. side as possible. As the most preferred example, points of

intersection between the optical axes of the input side and the

15   optical axes of the output side are set to be equivalent to lattice

points of a square lattice so that the movable mirrors 32 are

arranged at the lattice points respectively and adjusted in such

a manner that beam waists are formed on a diagonal line (cross

line a-a) of the square lattice. Incidentally, in Fig. 3, movable

20   mirrors expressed by the slanting lines among the large number

of movable mirrors are performing light reflecting operation.

When the operation of each movable mirror is controlled, the

optical path can be switched to a desired one.

Examples of the optical module according to the present

25   invention may include: an optical demultiplexer module in which

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a filter is used as the optically functional portion while a single collimator is disposed on the input side and a plurality of collimators are disposed on the output side; an optical multiplexer module in which a filter is used as the photofuctional

5   portion while a plurality of collimators are disposed on the input side and a single collimator is disposed on the output side; an optical tap module using semi-transparent mirrors as the optically functional portion; and so on. Also in each of these modules, the variable characteristic parameters are changed

10   so that the position and size of the beam waist in one collimator is made as coincident with those in another collimator as possible.

       Fig. 4 shows an example of a three-port optical module constituted by a combination of a fiber collimator with two fibers and a fiber collimator with single fiber. Light emitted from

15   one 40 of two optical fibers which are fixed to one capillary and which are parallel to each other is magnified by a first lens 42. The light is reflected by a plane optical device (filter) 44 and condensed by the first lens 42. Thus, the condensed light enters the other optical fiber 46. Light transmitted through

20   the optical device 44 is condensed by a second lens 48. Thus, the condensed light enters the optical fiber 50. The optical device (filter) 44 is disposed at the focal point of the first lens 42. Beam waists as equal to one another as possible are formed on the reflection surface of the optical device (filter)

25   44 by all the fiber collimators. In this case, end surfaces

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of the two fibers are located at the other-side focal point of
the first lens. An optical demultiplexer can be achieved by
the aforementioned configuration. If the input side and the
output side are replaced by each other, an optical multiplexer
5 can be achieved by the same configuration as described above.

A semi-transparent mirror may be used as the optical device
44. In this case, an optical tap can be configured to have the
input-output relation the same as that in the optical multiplexer.
Also in this case, beam waists as equal to each other as possible
10 are formed on the optical device by all the fiber collimators.

Although the respective embodiments have shown the case
where fiber collimators are used both on the input side and on
the output side, the present invention may be applied also to
the case where a combination of a light-emitting device such
15 as a laser diode and a collimator lens is used on the input side,
the case where a combination of a collimator lens and a photodetector
such as a photodiode is used on the output side, and so on.

[Effect of the Invention]

As described above, in accordance with the present invention,
20 at least one collimator constituting an optical module is made
different from the other collimator in at least one variable
characteristic parameter. Hence, an optical module which is
small in size, low in insertion loss and low on insertion loss
deviation to obtain optimum optical coupling can be achieved
25 in the case where channels or ports are different from one another

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in free space length.